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Review

The Maturing Interdisciplinary Relationship between Human Biometeorological Aspects and Local Adaptation Processes: An Encompassing Overview

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Received: 10 October 2019; Accepted: 22 November 2019; Published: 25 November 2019

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Abstract: To date, top-down approaches have played a fundamental role in expanding the comprehension of both existing, and future, climatological patterns. In liaison, the focus attributed to climatic mitigation has shifted towards the identification of how climatic adaptation can specifically prepare for an era prone to further climatological aggravations. Within this review study, the progress and growing opportunities for the interdisciplinary integration of human biometeorological aspects within existing and future local adaptation efforts are assessed. This encompassing assessment of the existing literature likewise scrutinises existing scientific hurdles in approaching existing/future human thermal wellbeing in local urban contexts. The respective hurdles are subsequently framed into new research opportunities concerning human biometeorology and its increasing interdisciplinary significance in multifaceted urban thermal adaptation processes. It is here where the assembly and solidification of 'scientific bridges' are acknowledged within the multifaceted ambition to ensuring a responsive, safe and thermally comfortable urban environment. Amongst other aspects, this review study deliberates upon numerous scientific interferences that must be strengthened, inclusively between the: (i) climatic assessments of both top-down and bottom-up approaches to local human thermal wellbeing; (ii) rooted associations between qualitative and quantitative aspects of thermal comfort in both outdoor and indoor environments; and (iii) efficiency and easy-to-understand communication with non-climatic experts that play an equally fundamental role in consolidating effective adaptation responses in an era of climate change.

Keywords: human biometeorology; thermal comfort; interdisciplinarity; climate change adaptation; thermal sensitive design

1. Introduction

Before the turn of the century, the limited local specificity of global top-down approaches to climatic risk factors within urban environments was already well known by the international scientific community. In particular, such fragility in applicative know-how led to the growing interest in identifying how local bottom-up approaches could be instigated. As a result, and likely associated to the contiguous maturing Climate Change Adaptation (CCA), there has been a rapidly growing interest in how adaptation tools can be locally instigated to improve the climatic responsiveness of the urban public realm, e.g., [1–14].

Moreover, when considering the urban climate condition and human wellbeing within public realm, the scientific community has already recognised the growing importance of bottom-up approaches to climatic risk factors that are already presenting aggravations associated to climate change impacts [15–19]. For this reason, and as exemplified by studies undertaken by [12,20–24] local scales are becoming an arena in which both decision makers and designers are seeking means to address physiological and psychological factors pertaining to human thermal comfort within the public realm in an era of climate change.

Although examinations pertaining to the characteristics of the urban climate date well back to the previous century, e.g., [25–31], the practical application upon contemporary practices of urban design and planning has been limited [3,17,32,33]. Such a desire on behalf of the scientific community to further develop climatic tools can be intertwined with the earlier encompassing perspective of Wilbanks and Kates [34] who suggested that "the bulk of the research relating to local places to global climate change has been top-down, from global toward local, concentrating on methods of impact analysis that use as a starting point climate change scenarios derived from global models, even though these have little regional or local specificity. There is a growing interest, however, in considering a bottom-up approach, asking such questions as (. . .) how efforts at mitigation and adaptation can be locally initiated and adapted" (p. 1).

Such scientific interrogations chronologically coincided with the international recognition that mitigation efforts alone were no longer sufficient to address the potential impacts of climate change. Resultantly, the turn of the century witnessed an exponential leap for CCA efforts. Almost twenty years onwards, the demand for local application orientated approaches and tools are at an all-time high, both at assessment and at design levels. Within local scales, these assessments are predominantly focused upon the concrete symbiotic relationship between that of built form and encircling atmospheric conditions beneath the Urban Canopy Layer (UCL). Subsequently, it is here where the planning and design of the public realm and indoor environments can serve as a niche for interdisciplinary bottom-up approaches that question how efforts at adaptation can be locally initiated and adopted.

2. Review Structure

Within the scientific community, the balance between research articles and review articles discloses the encompassing ambition to develop existing knowledge, and at the same time, continually organise, review and structure the state-of-the-art. The objective of this study falls within the latter category, and aims to present an encompassing overview of the growing interdisciplinary relationships and interrogations concerning human biometeorological aspects associated to the practice of local thermal adaptation efforts. Divided into three predominant sections, the study situates: (i) the investigative prospectus for human biometeorology within the ever consolidating CCA agenda; (ii) the opportunities to further develop existing thermo–physiological approaches to identify both existing and future thermal risk factors that jeopardise urban wellbeing in indoor/outdoor settings; and, (iii) existing approaches and creative means to improve the thermal responsiveness of the urban environment through thermal sensitive urban design and planning efforts within local scales. Aiming to transition from the broader to the more specific facets of disclosed interdisciplinary relationship between human biometeorology and that of thermal adaptation processes, a summary of this division is presented in Figure 1.

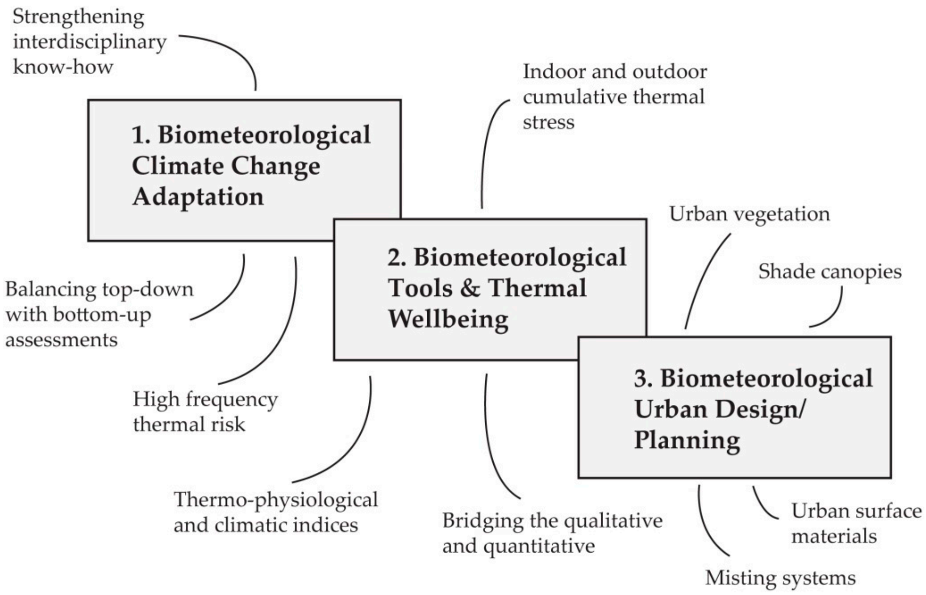


Figure 1. Structure schematic of review throughout the three sequential sections presented in the study.

Within each of the sections, the opportunities presented by human biometeorology to enhance local bottom-up adaptation processes are identified. In Section 2, and within the scope international CCA, based upon the unequivocal and direct thermo–physiological affects climate change shall have upon the human body, current methods, warning systems and impact projection assessments are discussed. Based upon local scales and recognising the increased need to go beyond 'high-impact but low frequency' impact projections; biometeorological tools to address the high frequency thermal risk factors are adjacently reviewed. Subsequently, and again with an emphasis on strengthening interdisciplinary bridges, this section moreover discusses the better integration and recognition of qualitative and quantitative aspects of thermal comfort in wholesome thermal comfort evaluations. Interconnected with the previous two points, the review study deliberates upon the fundamental transient associations between comfort thresholds and urban indoor and outdoor contexts. Lastly, and in direct association to local scales and how they can be feasibly modified through creative and flexible thermal sensitive adaptation processes, different existing measures to address local thermo–physiological risk factors in the urban public realm are reviewed. These disclosed measures are considered to be a part of a newly emerging scope for practices such as urban design and planning as a result of the effective bridging with local human biometeorology.

Overall, and throughout this review study, it is argued that the successful approach towards these factors highlights the growing significance of interdisciplinarity between different fields of practice. Ultimately, it is this assembly and fortification of collaborative scientific bridges that will bring different professionals together to tackle the same pressing issues within the urban environment. Naturally, while both scientific existing outcomes and obstacles are identified within the existing state-art-of-the-art, such obstacles are correspondingly framed into scientific opportunities to expanding interdisciplinary mentality/know-how regarding human biometeorology, and moreover, its unequivocally growing prominence in urban adaptation processes.

3. Biometeorological Climate Change Adaptation

Well before the turn of the century, and inclusively prior to the arrival of the CCA, Oke [35] identified that "relatively little of the large body of knowledge concerning urban climate has permeated through to working planners (. . .) the reasons for this state of affairs are many, but amongst those most cited are the inherent complexity of the subject, its interdisciplinary nature and lack of meaningful dialogue between planners and the climatological research community." (p. 1). Today, and even with growing consolidation of the CCA, the adjacent enclosure of pertinent biometeorological data and information within municipal and policy documents has been a complicated and a slow process.

3.1. Strengthening Interdisciplinary Know-How

In an earlier study conducted by Alcoforado and Vieira [36] that identified that within the Portuguese context, many cities presented a significant lack of pertinent meteorological data that could otherwise inform such local thermal adaptation efforts. Through the analysis of 15 master plans of urban municipalities, the respective study identified that although climatic information was considered in almost all of them, the information often proved either unreliable, or of little use for local adaptation efforts. Such a discrepancy was later argued by Alcoforado, Andrade, Lopes and Vasconcelos [17] to be attributable to numerous causes, including that the meteorological data from typical stations used in such plans were not applicable for microclimatic studies. Such a conclusion goes back to the prior conclusions of Oke [35], who additionally pointed at the difficulty in translating such information into robust tools for concrete local urban planning. Naturally, such difficulty is further increased at municipal policy and guideline levels.

Nevertheless almost two decades into the twenty-first century, and still within the Portuguese context, although further interdisciplinary strengthening is still considered essential [16], promising interest and integration with municipal entities are starting to be established [37]. This establishment can be inclusively associated to the scientific disseminations of the 'Climate Change and Environmental Systems Research' (CEG/CliMA) group. A group that has thus far conducted research into numerous topics, including overall bioclimatic conditions within Lisbon [38,39], causalities and intensities of Urban Heat Island (UHI) effects [18,40,41], urban wind patterns [42,43] and potential climatic integration within planning policy [15,44].

The exemplified disseminations focused on Lisbon mark a clear progression in addressing Okes [35] early outlook. Nonetheless, and with CCA serving as a continually growing catalyst for interdisciplinary thermal adaptation efforts, the international growing interaction with non-climatic experts (e.g., urban planners/designers, architects and landscape architects) must be upheld to address local thermo–physiological risk factors, as identified in [2,3,11,33,45–53],

3.2. Balancing Top-Down with Bottom-Up Assessments

As already mentioned, the international scientific community has already recognised the crucial role of bottom-up approaches that focus upon the importance of local scales. Although top-down approaches and disseminations have presented an imperative emerging international co-operative understanding of the existing and future global climatic system, such outcomes are rarely capable (nor so intended) to provide guidance at local scales. Resultantly, the amount of disseminated studies on this topic has increased dramatically since the turn of the century. In accordance, both the limitations and means to improve local scale analysis tools have grown across different disciplines such as urban climatology, and urban planning/design.

So far, and in accordance with Global Circulation Models (GCMs), global temperatures shall continue to rise throughout the 21st century. Yet, it has adjacently been recognised that such top-down climatic assessments are often less useful for local scale analysis tools and adaptation. For instance, within the assessments reports of international entities such as the Intergovernmental Panel on Climate Change (IPCC), the effects of weather are often described with a simple index based upon amalgamations of air temperature (T_a) and Relative Humidity (RH). Although it is indispensable to recognise the value of such descriptions within the maturing CCA agenda, when pondering upon bottom-up approaches to climatic vulnerability, the exclusion of vital non-temperature factors (i.e., radiation fluxes, wind speed (V) and human thermo–physiological factors) have been argued to decrease their usefulness for local thermal decision making and design [2,16,19,54,55].

In the study conducted by Matzarakis and Amelung [54], through the use of synoptic global radiation estimations retrieved from monthly sunshine fractions (extracted from the Hadley Centre's

HadCM3 model—one of the predominant models utilized by the IPCC in its third assessment report in 2001), clear underestimations of global climate change impacts on human thermal comfort thresholds were identified. As an example, Western European areas could witness changes in thermo–physiological indices by up to 15 °C based upon worst case scenarios. The synoptic projections sharply differ from the IPCC projections established upon singular climatic variables such as T_a [56,57]. Retrospectively, the significance of the study was twofold, it: (1) presented how the inclusion of non-temperature variables (i.e., radiation fluxes) could dramatically amplify the gravity of climate change projections; and, (2) showed an initial approach to running climate change scenario variables through a biometeorological model to understand how such variables would interact with the human body, and subsequently, obtain an estimation of thermo–physiological stress levels by the end of the century. Derivative from GCMs, and recognising the analogous limitations of standard climatic variables in weather forecasting activities, a recent study undertaken by Giannaros et al. [58] also emphasised the: (1) significance of human biometeorology in not only assessing present-day meteorological conditions, but warning provisions for both heat waves and cold outbreaks; and, (2) crucial role of effectively and accessibly communicating easy-to-understand to the general public.

Processed from GCMs, both studies conducted by Matzarakis and Amelung [54] and Giannaros, Lagouvardos, Kotroni and Matzarakis [58] marked clear strides in further consolidating the imperative role of human biometeorology in identifying and managing existing/future thermo–physiological risk factors. Subsequently, these strides also validate the continual importance of top-down assessments, even when specific local urban characteristics were not variables considered either study. More specifically, this was accomplished by the on-going robust emphasis upon: (i) frequently overlooked variables such as radiation fluxes; (ii) the symbiotic relationship with the human thermo–physiological system; and lastly, (iii) the critical role of the ease-of-assess, transmission and comprehensibility of the results for non-climatic experts and general public.

3.3. High Frequency Thermal Risk Factors

Contrastingly to the former studies, many top-down climatic disseminations (especially from international bodies), while fundamental, remain frequently "focussed [on] the exposure of cities to hazards that have a huge impact but low frequency. [They] have little to say about the high-frequency and microscale climatic phenomena created within the anthropogenic environment of the city" [59]. Contiguously, and as identified by numerous authors that address human thermal comfort through the elaboration of creative measures through urban planning and design, it is within the anthropogenic environment of the city where human wellbeing becomes crucial [13,60,61].

For this reason, it is here where "landscape architects and urban designers strive to design places that encourage [urban] activities, places where people will want to spend their time (. . .) however unless people are thermally comfortable in the space, they simply won't use it. Although few people are even aware of the effects that design can have on the sun, wind, humidity and air temperature in a space, a thermally comfortable microclimate is the very foundation of well-loved and well-used outdoor places." [23]. Analogous inferences were reached by the earlier study conducted by Whyte [29] who advocated that "by asking the right questions in sun and wind studies, by experimentation, we can find better ways to board the sun, to double its light, or to obscure it, or to cut down breezes in winter and induce them in the summer" (p. 45).

Respectively, and based upon the overarching principal that actual adaptation measures take place at finer scales, it is the concrete bond within specific localities which can substantiate such bioclimatic adaptation initiatives and tools in cities [1,13,55,62,63]. It is at this scale where the encircling microclimatic under the UCL that has direct 'in-situ' influences upon pedestrian comfort thresholds.

Undoubtedly, such principals enforce the fundamental relationship between resulting local climatic variables beneath the UCL, with that of human biometeorology. Under a more encompassing perspective, this suggests that urban form, layout and design have an enormous capability to enhance (or reduce) human wellbeing standards in cities. In this way, the interdisciplinary spheres of human biometeorology with that of climatic adaptation measures/tools must continue to be explored further.

4. Biometeorological Tools and Thermal Wellbeing

In accordance with the previously discussed scope of Oke [35], and the 'climate-comfort' rational discussed by Olgyay [30], this segment discusses the potentiality of interdisciplinarity in linking human biometeorology tools and assessments with local urban thermal wellbeing. The term 'locality' is again approached as the physical niche in which creative interdisciplinary practices such as Public Space Design (PSD) can render relevant, yet direct, thermal modifications of pedestrian thermo–physiological stress thresholds. Specifying this rational a little further in the greater context of local decision making and design, this catalyses two predominant perspectives, as suggested by Nouri, Costa, Santamouris and Matzarakis [3]: (i) the requirement to improve and facilitate the bioclimatic design guidelines within such environmental perspectives for local action and adaptation; and, (ii) given the growth of the CCA agenda, the accompanying cogency for local, thermal and pre-emptive climate-sensitive action and tools.

4.1. Thermo–Physiological and Climatic Indices

To undertake such an exercise, the direct effects of the thermal environment must be evaluated against the human biometeorological system. Such a multifaceted bond can be examined through the use of thermal indices that are centred on the energy balance of the human body [64]. Thus far, within the international community, a vast amount of thermal indices have been developed, and moreover, reviewed against one another. Examples of these studies are presented in Table 1.

Table 1. Example of studies that review and compare the application efficiency of different thermal indices in different settings.

No. of Investigated Indices	Dominant Focused Context	Region Specified	Year	Source
5	Not Stipulated	No	1988	[65]
2	Outdoor	Taiwan	2012	[66]
40	Outdoor	Mediterranean Zones	2014	[67]
162	Indoor/Outdoor	No	2015	[68]
3	Outdoor	Doha, Qatar	2015	[69]
24	Outdoor	Polar, Cold, Temperate, Arid and Tropical	2016	[70]
165	Indoor/Outdoor	No	2016	[71]
4 specific (from 165)	Outdoor	No	2018	[47]
6	Outdoor	No	2018	[72]
6	Outdoor	Mediterranean Zones	2019	[73]
6	Outdoor	Mediterranean Zones	2019	[74]
4	Indoor/Outdoor	No	2019	[75]
1 (MRT *1)	Indoor/Outdoor	No	2019	[76]
- (SVF *2)	Outdoor	No	2019	[77]

*1 MRT—Mean Radiant Temperature, *2 SVF—Sky View Factor.

Since the emergence of thermal indices well before the turn of the century, the international scientific community has since developed hundreds of different indices. Again, such an occurrence naturally leads to review and comparative studies of the indices themselves through different analytical methodologies and within different climatic contexts. Furthermore, and as exemplified by the studies undertaken by Golasi, Salata, Vollaro and Coppi [72], there still remain scientists that pursue the further standardisation of a global outdoor standardisation thermal indices. Although met with some resistance due to the already extensive amount and versatility of existing indices, such studies still salient the continual and important scientific desires to further develop additional approaches to human biometeorology. Adjacently, from the large identified sample of indices, many studies have suggested that only between 6 and 4 thermal indices can provide wholesome local human thermo–physiological evaluations [47,69,73–75]. In addition, and as a distinguished example from many related studies (discussed later in this section), the work undertaken by Lin, Tsai, Hwang and Matzarakis [66] presented important outputs pertaining to crucial relationships with microclimatic variables such as Mean Radiant Temperature (MRT) and Sky View Factor (SVF) ratios. Regarding these two aspects, and although the former two studies in Table 1 do not categorically refer to the comparison of thermal indices, both present noteworthy contemporary reviews regarding the calculation methods of: (i) MRT in indoor and outdoor environments through different applicative algorithms and models [76]; (ii) SVF through a diverse range of reviewed methodologies and software packages, moreover highlighting their respective weaknesses and strengthens within local microclimatic assessments and linkage with urban planning processes and decision making [77].

To illustrate a sample of the inherently different utilised thermal indices within the scientific community, and based upon the typological division suggested by Freitas and Grigorieva [68], of the eight, four typologies were included in Table 2, these being: (i) B–singular parameter model; (ii) C–climatic index based upon algebraic or statistical model; (iii) F–energy balance strain model; (iv) G–energy balance stress model.

Table 2. Illustration of selected thermal indices and their respective index typologies as defined by Freitas and Grigorieva [68].

Index	Acronym	Typology	Source
Perceived Temperature	(PT)	(G)–Energy balance stress model	[78]
Standard Effective Temperature	(SET *)	(G)–Energy balance stress model	[79,80]
Outdoor Standard Effective Temperature	(OUT_SET *)	(G)–Energy balance stress model	[63,81]
Thermal Humidity Index	(THI)	(C)–Algebraic/statistical model	[82]
Predicted Mean Vote	(PMV)	(G)–Energy balance stress model	[28,83]
Predicted Percentage of Dissatisfied	(PPD)	(G)–Energy balance stress model	[28]
Humidex	(HD)	(C)–Algebraic/statistical model	[84]
Index of Thermal Stress	(ITS)	(F)–Energy balance strain model	[31]
Outdoor thermal comfort model	(COMFA)	(G)–Energy balance stress model	[85,86]
Universal Thermal Climate Index	(UTCI)	(G)–Energy balance stress model	[87–89]
Wet Bulb Temperature	(WBGT)	(B)–Single-parameter model	[90,91]
Predicted Heat Strain	(PHS)	(F)–Energy balance strain model	[92]
Physiologically Equivalent Temperature	(PET)	(G)–Energy balance stress model	[26,93,94]
modified Physiologically Equivalent Temperature	(mPET)	(G)–Energy balance stress model *1	[95]

*1 New modified physiologically equivalent temperature (mPET) index included in (G) typology due to its close proximity to the original Munich energy-balance model for Individuals (MEMI).

Based upon the studies disclosed in Table 1, of the four typologies presented in Table 2, the predominantly utilized indices for outdoor studies have been those constructed upon the energy balance stress models, in particular, the Physiologically Equivalent Temperature (PET), Predicted Mean Vote (PMV), Universal Thermal Climate Index (UTCI) and Standard Effective Temperature (SET*) indices [96], especially for the climatic evaluation for urban planning and design [75].

In the case of the latter two examples in Table 2, of all of the thermo–physiological indices, PET has been one of the most commonly used steady-state model in human biometeorological studies [67]. Constructed upon the Munich Energy-balance Model for Individuals (MEMI) [97], it is designated as the T_a at which, in a typical indoor setting, the human energy budget is maintained by the skin temperature (T_{skn}), core temperature (T_{core}) and perspiration rate that are equivalent to those under the conditions to be investigated [93]. Retrospectively, the likely reason for its higher application can be attributable to: (i) its feasibility in being calibrated on easily obtainable microclimatic elements, and (ii) its measuring unit being (°C), which in turn, simplifies its comprehension by non-climatic experts, including urban designers/planners and architects. This being said, synonymous to the equally maturing body of knowledge in human biometeorology, numerous studies have already made headway in the development of the PET index as well. Directed specifically towards improving the calibration of the integrated thermoregulation and clothing models utilised by the PET index, Chen and Matzarakis [95] launched the new modified Physiologically Equivalent Temperature (mPET) index. As discussed in the study, the main modifications of the mPET are the integrated thermoregulation model (modified from a single double-node body model to a multiple-segment model) and updated the clothing model, resulting in more accurate evaluations of the human bio-heat transfer mechanism, particularly during periods of higher thermal stimuli. Such increased accuracy of the modified index was subsequently verified by numerous studies in different countries and climatic contexts [5,19,73,98,99].

4.2. Bridging the Qualitative with the Quantitative

As mentioned in the introduction, in addition to physiological aspects, there is also a demand in accompanying the associated call for investigating psychological factors of human thermal comfort. Although located predominantly within the qualitative spectrum, the 'intangible' attributes of human psychology have also been recognised to play a crucial role in diurnal human thermal comfort investigations. Such recognition has arisen at both in indoor contexts, e.g., [100–106], and outdoor contexts, e.g., [24,29,32,48,107–114].

Based upon a bottom-up perspective that focuses upon the role of local scales in ensuring human wellbeing during an era of climate change, Figure 2 illustrates the required interactions between that of: (1) Physiological aspects, which consider the direct quantitative influences of encircling microclimates upon the human-biometeorological system; (2) Psychological aspects, which prompts the adjacently important value of qualitative aspects of thermal comfort thresholds, including assessments of human behaviour patterns, and that of thermal adaptability; and lastly, (3) the interaction with further climate change impacts during the unravelling of the twenty-first century, that are already aggravating existing human thermal comfort standards. From the interaction of these three aspects, originates the requirement for further interdisciplinary biometeorological tools that can aid local assessment and design practices, both now, and in the future through informed CCA efforts.

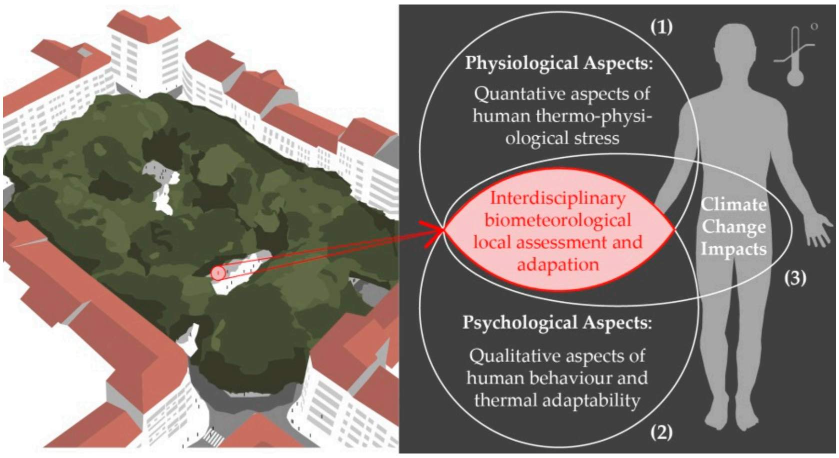


Figure 2. Illustrative division of human biometeorological facets within local scales based upon a bottom-up approach in century prone to climate change impacts.

Although the comparative significance between qualitative and quantitative aspects of thermal comfort is still debated within different studies (i.e., where some authors methodically favour one aspect more than the other), numerous veracities are concomitant to both schools of thought. To start with, it is consensus that there is an unmistakable opportunity to explore how specific qualitative aspects of thermal comfort can build upon quantitative assessments. Such an opportunity can be allied to a few simple premises, that: (i) predominantly in outdoor environments, human beings rarely pursue microclimatic monotony [109,115], reversely, it is the very desire of climatic diversity and stimulation (and even overstimulation beyond stipulated thermal comfort levels [108,111]) that also lures pedestrians outdoors [29]; (ii) human beings are by default peripatetic, meaning that their movement patterns are based upon complex behaviour and decision making processes associated to 'intangible' attributes (e.g., expectations, past experience, perceived control and time of exposure) [32,116].

As a result, improving this integration between these two aspects could potentially present means to better predict and account for human psychological attributes for local thermal sensitive design and planning. Of the attributes previously mentioned, it is suggested that these main attributes can open up new interdisciplinary lines of research, which by default, coerce the bridging with quantitative aspects of thermal comfort. In addition, such a bridging can also entice further considerations also interrelated to indoor conditions, as also suggested by past review studies exemplified by the prominent example disseminated by Brager and de-Dear [117]. As part of their review, they inclusively referenced an entire issue from *Energy and Buildings* [118] that focused upon the variation amongst the human psychological 'perceived need' or 'desire' for indoor mechanical air conditioning.

4.3. Indoor and Outdoor Cumulative Thermal Stress

In accordance with the human biometeorological evaluation study undertaken by Charalampopoulos, Tsiros, Chronopoulou-Sereli and Matzarakis [11] who utilised the PET index, two preliminary factors were adjoined, these being: (1) the PET Load (PETL), i.e., the amount of variation from the optimal physiological stress range (between PET values of 18–23 °C) as defined by [119,120]; and, (2) the cumulative PET Load (cPETL), i.e., the sum of the PETL for an *X* amount of hours which can be configured to represent a portion, or the full 24 hours of a respective day. Such an approach enables a preliminary understanding of cumulative human thermal stress loads beyond 'neutral' (or background) conditions. Although intended for outdoor assessments, principals of cumulative human thermal stress can also be transposed to methodically approach human psychological attributes, particularly during periods and/or events of accentuated thermal stress, and even climate change [19]. Subsequently, such accentuation periods with higher stimuli can be unambiguously associated to numerous urban events, particularly heatwaves. Alarmingly, and beyond the early consensus that increases in heatwaves are 'very likely' throughout the twenty-first century [121]; the subsequent fifth assessment report moreover stipulated that the influences of climate change upon heatwaves shall be more significant than the impacts upon global average temperatures [122].

Taking the European heatwave of 2003 as an extreme example which explicitly amplified the need for additional measures to warn, cope and prevent the recurrence of such events upon public health and welling [58,123,124]. Within Western Europe, the data provided by Nogueira et al. [125] identified that between the 29 July and 13 August 2003 within the district of Lisbon there was/were: (i) 15 days with a maximum T_a above 32 °C; (ii) a noteworthy consecutive run of 10 days with T_a above 32 °C; and, (iii) a 5 day period consecutively experiencing T_a above 35 °C. This extreme heat event led to severe implications on urban health, resulting in an estimated mortality rate increase of 37.7% in comparison to what would be expected under normal conditions.

Key lessons for human biometeorology can continue to be extracted from this type climatic event that has serious implications for human health and wellbeing in urban contexts. Such teachings, in turn, again call for more sophisticated integration and analytical tools between the quantitative and qualitative aspects of thermal comfort, both for outdoor and indoor environments. More specifically, and considering the early principals of the urban energy balance as defined by Oke [126] the reciprocal dynamics of indoor environments also play an essential role resultant of the: (i) increased heat storage within urban materials and buildings [18,22,40,127–131]; and the cause-and-effect of, (ii) anthropogenic emissions resultant of urban cooling energy loads associated to interior air conditioning [117,132–135], which by the end of the century can potentially increase by 166% (in energy demand) as a result of climate change [136].

In the case of naturally ventilated residential indoor environments during periods of extreme and extended heat stress, the principals of cumulative human thermal stress load can be strongly connected to psychological aspects. Although previously observed by Givoni [137] that "during periods of rising outdoor temperatures, e.g., a heat wave lasting for several days, the rate of rise of the indoor temperature is lower than that of the outdoors (. . .). As a result, the indoor temperatures during the heat-wave period will be somewhat lower" (p. 22), it is important to note that during extreme events, this 'somewhat' reduction while significant, is indicative of continued cumulative human thermal stress load during the night period. Such an extension, invariably, results in disruptions in human sleep cycles as a result of higher nocturnal indoor T_a levels [138,139]. These conclusions were also extended by a more recent review study conducted by Lan et al. [140], who also depicted upon the 2003 heatwave in Europe, and moreover, the associated future risk factors associated to human sleep disruptions as a result of climate change.

With regards to specific implications upon the human biometeorological system, the preceding study by Haskell et al. [141] indicated that T_a above the thermo–neutral thresholds increased wakefulness and decreases Slow Wave Sleep (SWS) which takes place in the late stages of non-Rapid Eye Movement ((n)REM). Such a stage is where energy restoration occurs, including the regulation of body glycogen levels, that are subsequently heavily consumed during active brain function [142]. Up until the more crucial and profound REM stage of sleep, the human body continues to thermo-regulate, and perspiration is proportional to the encircling thermal load [143]. During the latter stage of the sleep cycle, perspiration does not take place [144], and the human hypothalamic thermostat (in control of the body's T_{core}) becomes sedentary as a result of the poikilothermic state during the REM stage [145]. Resultantly, the successfulness in reaching REM sleep strongly depends upon the adequate down-regulation of T_{core} beforehand. If not accomplished, inclusively in circumstances with high thermal loads, both SWS and REM will likely be replaced by wakefulness to maintain bodily homeothermic conditions [146,147]. Such homeothermy can be backtracked to the functioning principals of the previously mentioned MEMI.

This being said, and in addition to heat stress, exposure to elevated nocturnal RH also plays a pivotal role in thermal stress. More specifically, increased RH levels impedes sweat to evaporate, thus impeding T_{skn} to dissipate heat and remain wet, thereby, suppressing adequate down-regulation of the body's T_{core}, and similarly decreasing the likelihood of REM sleep [147]. This influence of encircling nocturnal RH upon sleep quality has moreover been identified by other comparable studies, e.g., [140,148,149].

While suggested by prominent thermal comfort studies that people living in naturally ventilated buildings become accustomed to, and moreover grow to accept higher T_a and RH, [137], human biometeorological investigations have come to respectfully rebut such acclimatization easement (especially during periods of higher thermo–physiological loads). Respectively, and as identified by the early analysis undertaken by Libert et al. [150], heat-related sleep disruptions do not adapt even after five days of continuous diurnal and nocturnal heat exposure. Likewise, it was also later documented that the cerebral dynamics of SWS does not change after partial sleep deprivation (SD), where 'sleep pressure' would inevitably be augmented [151].

Subsequently, such results were also evidenced by the more recent study conducted by Nastos and Matzarakis [152] who analysed the daily records of SD against the frequency of daily weather conditions (with PET > 35 °C) and nocturnal conditions (with minimum T_a > 23 °C). The recorded events/admissions for SD were obtained from the psychiatric emergency unit of Eginition Hosptial of the Athens University Medical School during the years of 1989 and 1994. It is important to note that in this particular study, the SD admissions dataset did not include cases which were associated to specific organic disturbances. Such an inclusion would very likely increase admission data numbers; but invariably, excessively extend the investigation parameters due to the inherent intricacies of specific human organic disturbances in relationship with SDs (e.g., pertinent to the respiratory system [153], and in oncological cases [154]). Irrespectively, the study identified that during continued periods of both diurnal and nocturnal thermal load, there was a substantial increase in SD, which moreover, did not seem to placate, nor adapt, to the respective conditions over time.

Overall, the studies in this section depict upon the significance of the Circadian Rhythm Cycle (CRC) in human wellbeing, which by definition, also extends to the human biometeorological thermoregulation dynamics during the night. Naturally, the circumstances during the CRC influence wellbeing standards, whereby if one part of the cycle inept, there will be a cause-and-effect relationship upon the following stage. In other words, if the cumulative thermal loads do not fluctuate adequately to allow the human-biometeorological system to regulate, replenish and restore attributes of the human physiology (including during different sleep stages), then this shall have direct implications upon human psychology as well. In this way, the physiological and the psychological attributes pertaining to thermal comfort can be directly related to one another. It is here where central intangible aspects as of human psychology as presented by, e.g., [32] can be further explored, including for urban sensitive planning and design.

Inarguably, there still remain other noteworthy impromptu influences upon these intangible characteristics that influence human behaviour. However, it is argued that such qualitative thermal comfort aspects (e.g., expectations, past experience, perceived control and time of exposure) can be rendered less subjective by more efficiently cross-examining human behaviour patterns and decision making against CRC dynamics and cumulative thermal stress.

Evaluating the specific case-by-case peripatetic behaviour of individual human beings is very complex. Yet it is here reasoned that further studies on this interdisciplinary topic can be undertaken based upon the unambiguous certainties that are already held by the scientific community, including the: (1) universal conduct of the human biometeorological system to thermal stimulus (including in cumulative terms); and, (2) impacts that extreme urban events can have upon both indoor and outdoor environments upon urban human wellbeing, including those associated to future climatic aggravation. For this reason, when one considers the urban populace as whole, it feasible to acknowledge that pedestrians shall, in general, show higher psychological predispositions under certain climatic conditions, particularly under prolonged extreme events.

As represented in Figure 3, this shall not only affect the peripatetic transitioning between indoor and outdoor movement patterns/durations, but the individual psychological aspects that catalyse such human behaviour. More precisely, during periods of extended thermo–physiological stress, elicited from 'past experience' of thermal discomfort, there shall be a greater pursuit (i.e., 'expectation') to address cumulative discomfort. Since this is associated with the CRC, it cannot be assumed that thermal stress simply resets at the end of the day. Naturally, the longer the susceptibility to cumulative load (including throughout the night) the greater the 'expectation' and reduced willingness for more 'time of exposure'. Subsequently, and as developed throughout this section, it is suggested that there are opportunities for future concrete investigations to better link this symbiotic physiological and psychological relationship.

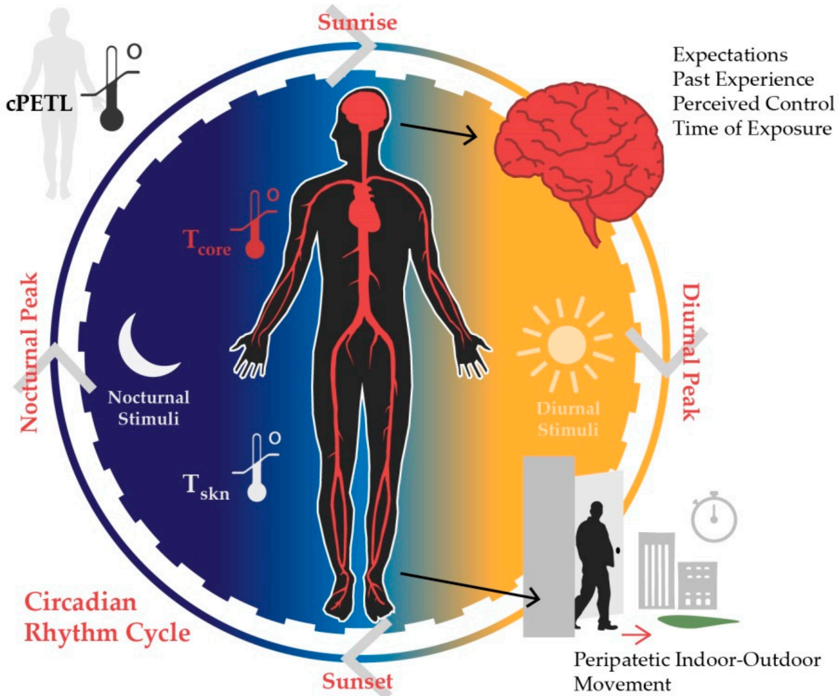


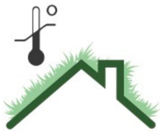
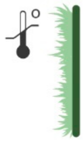
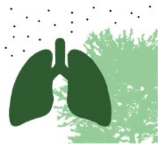
Figure 3. The relationship of the circadian rhythm cycle, cumulative stress and general psychological characteristics.

5. Biometeorological Urban Design/Planning

5.1. Urban Vegetation

So far within the existing literature, numerous review articles have already discussed the state-of-the-art of various aspects pertaining to the influences of vegetation upon urban climates. Of these review articles thus far, e.g., [3,20,128,155–159], the two predominant influences of vegetation pertaining to urban thermal comfort aspects have thus far been the: (i) direct reductions of urban T_a; and moreover the (ii) associated interrelating reduction of UHI intensities. Other disseminated review studies have moreover deliberated on further positive attributes that vegetation can have upon indoor/outdoor human wellbeing standards in urban contexts. Within Table 3, these review studies are divided into five summarised topics that also play an important role in ensuring urban environmental health and welfare.

Table 3. Selected review studies concerning further positive attributes of vegetation within urban environments.

No.	Predominant Review Topic Summary	Icon	Study Year	Example Review Studies
(i)	Specific effects of green roofs, including indoor thermal behaviour, cooling loads and performance		2014 2014 2018	[160] [161] [162]
(ii)	Specific quantitative influences and performance of urban green walls/facades		2014 2014 2017	[163] [164] [165]
(iii)	Air quality and particles dispersion/abatement through the presence of vegetation		2015 2015 2017	[166] [167] [168]
(iv)	Overall socio-economic benefits, and challenges, of growing urban vegetation in the public realm		2011 2015	[169] [170]
(v)	Wider social impacts of street vegetation upon urban ecosystems and communities		2016	[171]

(i) As suggested by the comprehensive review undertaken by Berardi, GhaffarianHoseini and GhaffarianHoseini [160] there is a very tactile opportunity to continue the exploration into the further quantification and assessments of interdisciplinary approaches regarding urban landscaping, plantations, construction and that of mechanical/environmental engineering. Moreover and in addition to stipulating the different classification of green roofs, the authors also cross-examined the typologies against their ability in mitigating UHI/air pollution, improve stormwater management, reduce urban noise and augment urban diversity. From the same year, and focused at the city scale, Santamouris [161] identified four categories to determine the particular efficiency of green roofs, namely through: (i) climatological variables, including radiation fluctuations; (ii) optical variables, including changes in albedo and absorptivity of the roof's vegetation; (iii) thermal variables, including thermal capacity and heat storage; and lastly, (iv) hydrological variables, including the dynamics of latent heat loss due to evaporation of the water vapour from the vegetative material (or in other words, evapotranspiration). Within the more recent study conducted by Shafique, Kim and Rafiq [162], it was revealed how green roofs can aid simulating urban natural hydrology systems, and also reduce factors such as UHI effects. Still within this recent study, the prominence of further interdisciplinary research was recognised, including in accompanying the demand for such technology through economically sustainable methods.

(ii) With regards to the application of green walls and facades, the review study conducted by Hunter, Williams, Rayner, Aye, Hes and Livesley [163] reported that their efficiency must be based on multiple microclimatic factors, including G_{rad}, T_a and V (both adjacent to the structure, and in-between the gap with the respective wall). In the summary of the study, while the significant potential of green facades were recognised in urban contexts, it was adjacently argued that: (i) they are unlikely mechanisms to modulate internal buildings in all types of construction typologies and climatic contexts; and, (ii) its associated engineering terminology is often too specific to be readily understood across design and planning disciplines. Similarly, and also relating the application of these vegetation structures to different climates, and moreover the influences of different vegetative species, Perez, Coma, Martorell and Cabeza [164] came to similar conclusions. Finally, and within the more recent review study conducted by Medl, Stangl and Florineth [165] (and in addition to the recognised positive attributes mentioned above), the authors argued that there still remains a clear need for further interdisciplinary and standardized measurement approaches to guarantee the better application and erection of effective urban green facades.

(iii) While the aforementioned studies also discussed issues of urban air quality and pollution dispersion through urban vegetation, Gallagher, Baldauf, Fuller, Kumar, Gill and McNabola [166] and Abhijith, Kumar, Gallagher, McNabola, Baldauf, Pilla, Broderick, Sabatino and Pulvirenti [168] took this analysis a step further. More specifically, it was identified that wind-tunnel and modelling results provide adequate evaluations, yet further real-world studies are still required to validate such findings. Similarly, and still in line with the aforementioned perspective of Oke [35], both studies moreover suggest that to develop clear guidelines for urban planners with regards to air quality and pollution dispersal; better interdisciplinary 'channels' must be fortified to enable such knowledge to be translated into practical guidelines to ensure their effective urban implementation. Convergent conclusions pertaining to the associated translation into urban planning and design tools/guidelines were also met by Janhall [167].

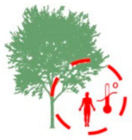
(iv) Undertaking a more socio-economic approach, the review study launched by Soares, Rego, McPherson, Simpson, Peper and Xiao [169] described the application of the Street Tree Resource Analysis Tool for Urban forest Managers (STRATUM) within Lisbon. The results of the study disclosed a clear quantitative breakdown of economic maintenance/managerial costs of urban vegetation species which was subsequently crossed examined with urban 'energy savings', air purification, increased property values, reduced stormwater runoff and CO2 emissions. Still predominantly within the socio-economic spectrum, the later review study undertaken by Mullaney, Lucke and Trueman [170] also provided an investigation into financial aspects of urban vegetation. More specifically, beyond also disclosing environmental and socio-economic benefits, the costs/management of detailed characteristics such as pavement damage from tree roots were also case-studied.

(v) In the last segment, the study conducted by Salmond, Tadaki, Vardoulakis, Arbuthnott, Coutts, Demuzere, Dirks, Heaviside, Lim, Macintyre, Mclnnes, and Wheeler [171] undertook a more encompassing perspective, which suggested that based upon the existing literature, there needs to be a locally based bottom-up decision making process. Such a process was argued to be innately better associated with local community engagement to better determine 'what matters to them', and not just constructed upon the technical scientific aspects of ecological interventions. As a result, a matured interdisciplinary relationship between these cultural and scientific approaches was suggested to be essential to further exploit the disclosed societal and wider benefits provided by urban vegetation.

Parting from review studies, and focussing henceforth on individual investigations regarding the specific relationship of human thermo–physiological thresholds with urban vegetation, two distinct types of studies can be established, those: (1) which focus upon the direct 'In-Situ' (IS) influences of vegetation directly upon the encircling area (such as beneath the vegetative crown); and, (2) which investigate the effects of Park Cooling Islands (PCI) resultant of urban vegetation amid different spaces (where normally one is labelled as an urban 'green space').

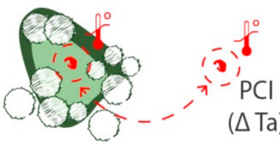
Both within the IS and PCI types of study, the methodical approach towards human thermal comfort thresholds have been different. Most prominently, there is a clear distinction between studies which have concentrated more upon singular variables (such as T_a), and those which have applied thermo–physiological indices that account for non-temperature variables, including radiation fluxes. Thus far, significant IS effects of urban vegetation specifically upon T_a and its associated connotations upon human thermal comfort have been well documented as exemplified in the studies in Table 4. Adjacently, studies focussing on the effects PCI upon T_a are successively presented in Table 5. Within these tables, the maximum thermal result obtained by the study, year, city and climatic context (through the Köppen Geiger (KG) [172] climatic classification system) are presented.

Table 4. Studies concerning in-situ (IS) changes in T_a resultant of urban vegetation.



Thermal Result (T_a Max)	Location	KG	Study Year	Source
−1.5 °C	California	*'Csa'*	1988	[173]
−0.7 °C	Tokyo	*'Cfa'*	2008	[174]
−2.2 °C	Athens	*'Csa'*	2010	[175]
−0.5 °C	Singapore	*'Af'*	2010	[176]
−1.0 °C	Melbourne	*'Cfb'*	2013	[177]
−1.0 °C	Manchester	*'Cfb'*	2014	[178]
Table Result Avg. = −1.2 °C				

Table 5. Studies concerning changes in T_a as a result of urban park cooling islands (PCI) effects.

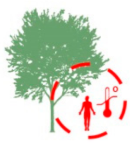


Thermal Result (T_a Max)	Location	KG	Study Year	Source
−4.0 °C	Mexico City	*'Cwb'*	1990-1	[179]
−2.5 °C	Dehli	*'BSh'*	1990-1	[180]
−3.0 °C	Kumanoto	*'Cfa'*	1991	[181]
−2.5 °C	Fukuoka	*'Cfa'*	1993	[182]
−2.0 °C	Tokyo	*'Cfa'*	1998	[132]
−4.0 °C	(Scaled model)	-	1999	[183]
−4.0 °C	Tel Aviv	*'Csa'*	2000	[184]
−4.0 °C	Botswana	*'BSh'*	2004	[185]
−3.5 °C	Tel Aviv	*'Csa'*	2006	[186]
−4.4 °C	Taipei	*'Cfa'*	2007	[187]
−2.5 °C	Taipei	*'Cfa'*	2010	[188]
−5.0 °C	Athens	*'Csa'*	2014	[189]
−5.0 °C	Chania	*'Csa'*	2014	[190]
−7.4 °C	Lisbon	*'Csa'*	2019	[191]
Table Result Avg. = −3.9 °C				

Between Tables 4 and 5, it is possible to identify that the studies have predominantly been undertaken within 'Temperate' climates, with variations mostly being discernable within the subcategories pertaining to both annual precipitation levels, and average temperature levels during the summer. Additionally, when considering the thermal effects in both Tables, the summarised averages of 'maximum thermal effects' present by the studies show clear thermal differences between IS and PCI typologies. As expected, this divergence can be attributable to the: (i) increased amount of vegetative mass within PCI studies that were able to have a greater impact upon elements such as atmospheric T_a and RH, which in IS studies were easier to dissipate in the atmosphere before allowing the utilised apparatus to record such modifications; and (ii) distances between the study's measurement locations, which in the case of the some PCI studies could vary up to hundreds of metres, thus entailing other potential microclimatic influences (e.g., sufficiently notable morphological and topographical disparities, rendering urban corridor cooling effects through channelled *V* acceleration and *V* gusts).

Adjacently to these T_a studies, aspects of urban vegetation as a tool address and regulate human thermal comfort in urban environments through non-temperature factors have also been discussed extensively. Such factors included the direct role urban tree crowns reducing the amount of radiation reaching pedestrian levels [192–196]. Subsequently, this was followed by studies which focused upon assessments that included non-temperature dynamics through the use of human biometeorological models and indices in both IS studies (Table 6) and PCI studies (Table 7).

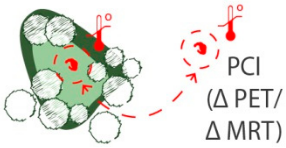
Table 6. Studies concerning IS changes in physiologically equivalent temperature (PET)/ mean radiant temperature (MRT) resultant of urban vegetation.



IS (Δ PET/ Δ MRT)

Thermal Result (PET/MRT Max)	Location	KG	Study Year	Source
−11.2 °C (PET)	Szeged	*'Cfb'*	2006	[197]
−12.0 °C (PET)	São Paulo	*'Cfa'*	2008	[198]
≈−12.0 °C (MRT)	Huwei	*'Cfa'*	2010	[199]
−20.0 °C (PET)	Shanghai	*'Cfa'*	2011	[200]
−8.0 °C (PET)	Campinas	*'Cwa'*	2012	[201]
−8.3 °C (PET)	Athens	*'Csa'*	2012	[33]
−16.6 °C (PET)	Campinas	*'Cwa'*	2015	[202]
−27.0 °C (MRT)	Manchester	*'Cfb'*	2016	[203]
−4.6 °C (PET)	Toronto	*'Dfb'*	2016	[22]
−3.4 °C (PET)	Hong Kong	*'Cwa'*	2017	[204]
−9.9 °C (PET)	Lisbon	*'Csa'*	2017	[108]
−15.6 °C (PET)	Lisbon	*'Csa'*	2018	[99]
Table Result Avg. = −11 °C (PET)/−19.5 °C (MRT)				

Table 7. Studies concerning changes in PET/MRT as a result of urban PCI effects.



Thermal Result (PET/MRT Max)	Location	KG	Study Year	Source
−17.6 °C (PET)	Freiburg	'*Cfb*'	2003	[205]
−9.0 °C (PET)	Freiburg	'*Cfb*'	2006	[206]
−33.0 °C (MRT)	Lisbon	'*Csa*'	2007	[207]
−10.7 °C (PET)	Tel Aviv	'*Csa*'	2010	[208]
−39.2 °C (MRT)	Lisbon	'*Csa*'	2011	[209]
−12.0 °C (PET)	Tel Aviv	'*Csa*'	2012	[210]
−20.0 °C (MRT)	Milan, Genoa, Rome	'*Cfa*', '*Csa*', '*Csa*'	2014	[211]
−10.0 °C (PET)	Toulouse	'*Cfb*'	2016	[212]
−18.0 °C (PET)	Tel Aviv, Beer Sheva, Eilat	'*Csa*', '*BSh*', '*BWh*'	2017	[4]
Table Result Avg. = −12.3 °C (PET)/−30.7 °C (MRT)				

Both IS and PCI studies that included non-temperature variables revealed very important differences, that can be related back to the outcomes also obtained by Matzarakis and Amelung [54] due to the crucial importance of radiation within thermal comfort studies and projections. In comparison with the former maximum T_a averages from Table 4 (–1.2 °C) and Table 5 (–3.9 °C), PET calculations revealed average maximum reductions of –11.0 °C for IS studies and –12.3 °C for PCI studies. Furthermore, it is worth noting the elevated changes in MRT with a maximum reduction of –39.2 °C obtained by Oliveira, Andrade and Vaz [209]. Such a measurement was undertaken within a small urban park in Lisbon and compared with values presented by the local meteorological station during August 2007. It is worth noting that during the same assessment period/day, the identified difference of T_a was of –3.2 °C.

When considering the differences of obtained PET/MRT measurements between the IS and PCI studies, the changes were more modest. However (and unlike in the case of T_a studies) it is suggested that such difference are less associated to IS/PCI study typology, and more attributable to the type of tree species used in each study. As identified by numerous studies, e.g., [213], the biggest influence upon thermo–physiological impacts from urban trees is associated to tree species, rather than planting layout.

This being said, the type and quantification of the influences on human biometeorology resultant of urban vegetation also greatly depends upon the proposed evaluation methods and assessment scale. Naturally, between the disclosed studies in Table 4 through to Table 7, the applied methodologies on behalf of the authors varied. Yet general trends amongst these studies are clearly identifiable. Such trends in summary demonstrate that PCI effect studies render greater reductions in singular variables due to the larger cluster and/or arrangement of vegetation mass within the designated 'green space'. Although much more modest, the same can be recognised for studies which utilised thermo–physiological variables in PCI assessments. While both types of studies have rendered important outcomes, it is suggested that those which considered reductions in radiation fluxes upon the human biometeorological system are able to present more wholesome evaluations of human thermal wellbeing.

5.2. Shade Canopies

Within the existing literature, numerous studies have also acknowledged the critical role between urban canyons, radiation fluxes and human biometeorological thresholds [5,12,214–218]. Resultantly, when considering the application of shade canopies within local scales, the main microclimatic factor that must be investigated is the structures ability to attenuate solar radiation. In IS terms, while recorded T_a beneath a canopy may be the same as a recording fully exposed to the sun, the amount of solar radiation can vary significantly [16,60,108].

Unlike in the aforementioned studies, the majority of the application of (either ephemeral or permanent) shade canopies in the urban realm has not considered the specific impacts upon the human biometeorological system. Inversely, they more frequently originate from artistic influence (particularly ephemeral solutions) and more-often-then-not thermally impassive urban amenity placement. Resultantly, the current application of shade canopies as an effective thermal attenuation measure typology must be reconsidered, especially in the case of permanent solutions due to risks of over-shading during colder months.

5.3. Urban Surface Materials

Returning again to the principals of the urban energy balance, elements such as local surface materials play a large role in urban heat storage patterns. As a result, and due to the vast amount of paving within the public realm, its heat flux and implications on human biometeorology has been extensively discussed within the existing literature. More specifically, and due to the consensually recognised poor thermal performance of urban materials such as asphalt and concrete, means to augment surface albedos are continually being explored. As suggested by the study undertaken by Gaitani et al. [219] both researchers and manufacturers are already been developing 'cool' materials with higher reflectance values compared to the conventionally pigmented materials of the matching colour. In addition, such materials have been considered in local sites where the use of light colours could lead to solar glare issues, thus rendering another type of human discomfort within the public realm. Such efforts fall within a strong growing body of existing literature which consider divergent methods (including the implementation of 'infrared reflective cool paint' and 'photocatalytic compounds') to increase the thermal behaviour of pavement materials [129,130,220–226].

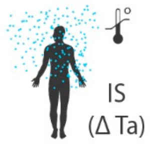
Retrospectively, considering the existing state-of-the-art, the relationship between human thermal comfort thresholds and surface materials should be approached as a two-step sequential approach. Whereby the assessment and design of pavements through interdisciplinary urban planning/design processes should: (1) be integrated with other measures that can, beforehand, reduce the energy load upon street materials; and subsequently, (2) ensure an effective thermal balance of the material itself by considering factors such as absorbed radiation, emitted infrared radiation, heat storage/convection and the effects of anthropogenic heat caused by urban activities such as vehicular traffic.

5.4. Misting Systems

The application of water and misting systems within the urban public realm has been a measure typology which was witnessed an increasing change in paradigm. In other words, cooling purposes behind that of pure aesthetics are increasingly becoming more obvious in urban environments. As a result, they are moreover growing in applicative meaning within interdisciplinary CCA efforts to improve local thermal conditions at local scales [227,228].

So far within the state-of-the-art, there is a fairly observable division within existing projects that use water or misting systems to improve thermal comfort levels during the hotter periods of the year. The first cluster, more often orientated towards bioclimatic design approaches [227,229,230], often lack the mechanical background in concretely attaining the correct balance between RH and T_a to cool microclimates without exacerbating acceptable atmospheric moisture levels. On the other hand, the second cluster can be linked back to the rudimentary, yet effective, Japanese cultural cooling method called 'Uchimizu' [231]. Correspondingly, with time, the simple action of scattering of water upon the entrances of residential buildings has evolved, and rendered Japan as one of the frontrunner countries in this cluster. Congruently with the Japanese nocturnal thermal comfort studies previously mentioned in this article, the focus upon diurnal/nocturnal equilibrium between T_a and RH can largely be attributable to Japan having simultaneously elevated humidity levels and temperatures, including during the summer [172]. As a result, the application of 'dry-mist' technology both within indoor and outdoor environments has been extensively researched within Japanese cities as demonstrated in Table 8.

Table 8. Exemplification of Japanese misting system studies originating from ancient 'Uchimizu' concepts to specifically reduce encircling T_a levels.



Thermal Result (Ta Max)	Location	KG	Study Method.	Study Year	Source
–2.0 °C	Nagoya	*'Cfa'*	Field Study	2008	[232]
–1.5 °C	Tokyo	*'Cfa'*	Field Study	2008	[233]
–2.5 °C	Tokyo	*'Cfa'*	CFD * Study	2008	[234]
–2.0 °C	Yohohama	*'Cfa'*	CFDStudy	2009	[231]
–0.8 °C	Osaka	*'Cfa'*	Field + CFD Study	2011	[235]
Table Result Avg. = –1.8 °C		* CFD—Computational Fluid Dynamic			

Based upon KG classification climates concomitant with 'temperate' yet with hot and wet summers, the outputs from the Japanese studies have marked an important step forwards in addressing how misting systems can be specifically configured to reduce T_a, without exacerbating local atmospheric moisture content in the air. Similar to the average maximum reductions in T_a as presented in Table 4 discussing the IS reductions as a result of urban vegetation, Table 8 presented a comparable result of –1.8 °C. This being said, this second cluster of measures has the problem of being extensively orientated towards engineering approach, with limited or no design connotations. Such a lapse between the engineering spectrum with design applications reinforce the aforementioned conclusions reached by the review study conducted by Hunter, Williams, Rayner, Aye, Hes and Livesley [163] regarding urban green walls and façades.

Subsequently, there needs to be a better interdisciplinary integration of these two clusters, where design and engineering approaches combine to tackle issues of human thermal comfort. Encouragingly, there have already numerous bioclimatic studies which have provided both conceptual, e.g., [108] and constructed, e.g., [115,236] examples of how water can be used to cool the human-biometeorological system without exacerbating encircling atmospheric moisture levels. Nevertheless, there still remains a large opportunity for future studies to continue to dilute the disparity between these two clusters, even if initially based on rudimentary atmospheric principals.

6. Concluding Remarks

Within the contemporary city, the interdisciplinary relationship between biometeorology and local adaptation has already made important progress in addressing urban thermal wellbeing and safety. This being said, and as recognised within the three interconnecting sections of this encompassing review study, there remains the opportunity to further communicate climatic information into urban thermal planning/design tools and assessments. As further advocated by the adjacent review studies discussed in this study, the interdisciplinary transposal of technical know-how into concrete adaptation tools needs to be enforced. Pertaining specifically to urban human biometeorological aspects with that of urban wellbeing, an encompassing schematic summary is illustrated in Figure 4.

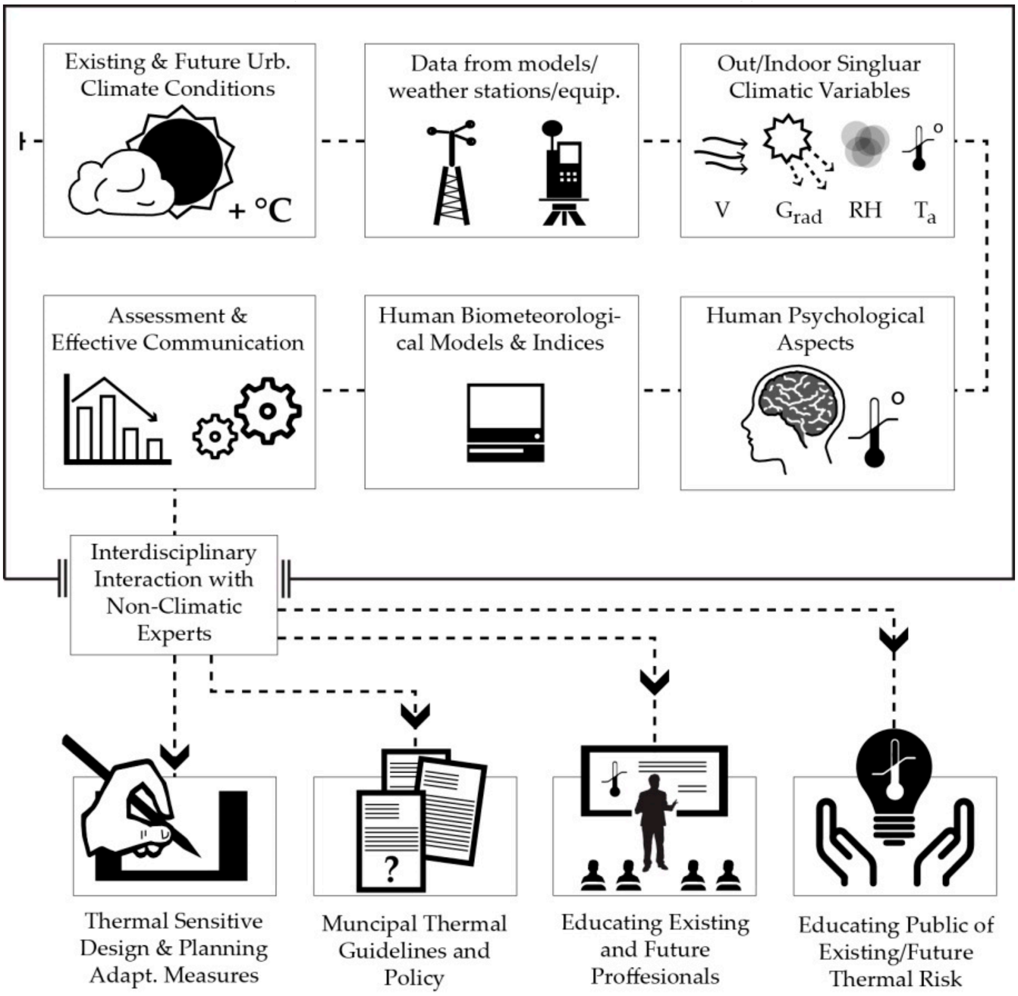


Figure 4. Schematic overview of human biometeorological aspects and augmenting associated interdisciplinary communication with non-climatic experts.

As discussed within the first section of the study, human biometeorology must play an increased role within existing and future thermo–physiological assessments of urban climate conditions. More specifically:

1. Methods of approaching climatic data from climatic models and meteorological stations/equipment should not rely solely upon singular climatic variables to obtain wholesome evaluations of existing or future human thermal comfort conditions as a result of climate change.
2. The information retrieved from such assessments must, unequivocally, be translatable through easy-to-understand guidance for non-climatic experts, and that of the general public. Such interdisciplinary communication channels shall become moreover significant given the expected increase of extreme heat/cold events within urban contexts. Eventually, the sequential multifaceted process of going from identified risk factors, to establishing better thermal response measures and transposing these into municipal climatic policy and guidelines can be strengthened.
3. Due to the inherent nature of thermo–physiological risk factors, undertaken assessments and projections must reach a better equilibrium between 'huge-impact-but-low-frequency' with that of 'high-frequency-yet-continuous' stimulus within the built environment, particularly during

summer/winter periods. In this way, thermal sensitive urban planning and design can better tackle both of these different, yet, decisive facets of urban climatology.

As discussed within the second segment of the study, further interdisciplinary scientific bridging must be accomplished between:

1. The remarkable and continual evolution of different thermo–physiological indices (including those arising from energy balance stress models, energy balance stain models, statistical/algebraic models and single-parameter models) with that of psychological factors. As mentioned, as this remains a less explored characteristic, this originates the respective opportunity to decrease 'qualitative subjectivity' through further research. Such research outlines can be launched through the association between continued physiological cumulative stimulus, circadian rhythm cycles, and anticipated triggers of human psychological behaviour patterns.
2. In association to the previous point, such future lines of research shall also diminish the often over-powering differentiation between evaluation methods between outdoor and indoor environments. Although clear why thermal evaluation methods must be different between these environments, the analytical relationship between the two types of environments must be strengthened. As an example, the effects existing/future extreme heat events shall influence both outdoor and indoor environments; meaning that the daily peripatetic transient relationship between the two environments can be better explored in future thermal comfort research. As result, this shall once again present better means of establishing better thermal response measures, both in indoor and in outdoor contexts.

Within the final section of the study, an overview of existing biometeorological aspects has already been integrated within different typologies of local thermal responsive measures. Such efforts are expected to propagate as the climate change adaptation agenda further matures its approaches and tools to present bottom-up means to attenuate thermo–physiological factors during the twenty-first-century. This being said, the final section of the study also discussed means in which human biometeorological aspects can more concretely aid local bottom-up adaptation processes through thermal sensitive design and planning. Beyond the recurring recognition from the disclosed review and research articles calling for further interdisciplinary communication amongst engineering/technical climatic know-how and urban planning-design tools, it was moreover acknowledged that:

1. While singular-variable evaluations pertaining to the thermal benefits of urban vegetation have been vital for thermal comfort studies (including in both IS and PCI typologies), the exclusion of non-temperature variables limit thermo–physiological interface comprehension with the human biometeorological system.
2. Given that the biggest potential of shade canopies is to limit the amount of global radiation projected upon the human body, the very limited amount of existing studies examining this aspect needs to be addressed by future research. Here, material types, structure size and distribution can all serve as analytical variables for addressing thermal comfort in open spaces that are particularly susceptible to high amounts of radiation. Ironically, the scientific community has produced a very strong body of research concerning the relationship amongst different urban morphological compositions and that of solar radiation. As a result, a rich body of research into which types of street configurations and orientations will serve as an excellent platform to guide such future research.
3. Due to the predominant use of thermally poor preforming materials, (such as urban concrete and asphalt) within cities, while there has been a considerable amount of research into surface materials, there is the opportunity to further explore the application of thermally efficient pavement materials. While existing studies have made clear strides in examining individual material, aggregate and finishing performances, there needs to be further studies that link such materials with other measure typologies within urban fabrics. As an example, there is the prospect

to further examine the affiliation with shading patterns resulting from both tree crowns and shading amenities. Since both of these measures can be utilised to reduce the amount of absorbed solar radiation upon a specific type of investigated pavement, the resulting inferences upon emitted infrared radiation, heat storage and convections can be further explored under specific urban conditions/layouts. Such studies will propagate means to address high surface temperatures and inefficient albedos values in local thermal urban planning/design and decision making.

4. As a result of the remaining disparity between engineering and design approaches to misting systems within the urban realm, similar to the case of shade canopies, there needs to be additional studies that consider wholesome projects which consider actual influences upon the human biometeorological system. Although commonly found within cities, there is a large opportunity for future studies to continue to dilute the segregation between engineering and thermal sensitive design approaches, even if based upon simple atmospheric principals to accomplish their full potential in attenuating thermal comfort stress without exacerbating atmospheric moisture content levels.

Overall, while the scientific community has made large strides in thermal comfort studies which were arguably catalysed by the maturing CCA agenda, there still remains a fertile opportunity for more scientific investigation. Inclusively, this review article suggests that this scientific advancement shall always be synonymously concomitant with interdisciplinarity. In other words, while the deepening of knowledge within a specific field is a quintessential cornerstone to science, the same can be said for the bridging between different disciplines that, are ultimately, set to face similar challenges throughout the twenty-first century. As it stands, the interdisciplinary interaction with non-climatic experts is still not strong enough, or at least, nowhere as strong as the existing thermal assessment capacity of climatological related experts. Again summarised in Figure 4, this fragility arguably risks the weakening of: (i) the concrete know-how of architects, landscape architects, urban designers and planners to more efficiently address human biometeorological constraints, and suggest local bioclimatic measures to address both indoor and outdoor human wellbeing standards; (ii) municipal policy and guidelines that could otherwise aid thermal sensitive design and planning; (iii) the transposition of knowledge to other non-climatic experts such as students to catalyse this interdisciplinary bridging upon upcoming generations of scientists and professionals; and finally, (iv) the production and dissemination of easy-to-use, easy-to-understand information and warning mechanisms for the general public regarding urban climatic risks on wellbeing standards, and just as importantly, the augmentation of such risk factors as a result of climate change.

Author Contributions: The authors declare that each has contributed equally to the production of this document. Whereby, (i) A.S.N. consolidated the overall results obtained within the study; and (ii) A.M. equally provided both general and specific contributions to the scientific content elaborated within this review study.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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